

CS 145 Final Review

The Best Of Collection (Master Tracks), Vol. 2

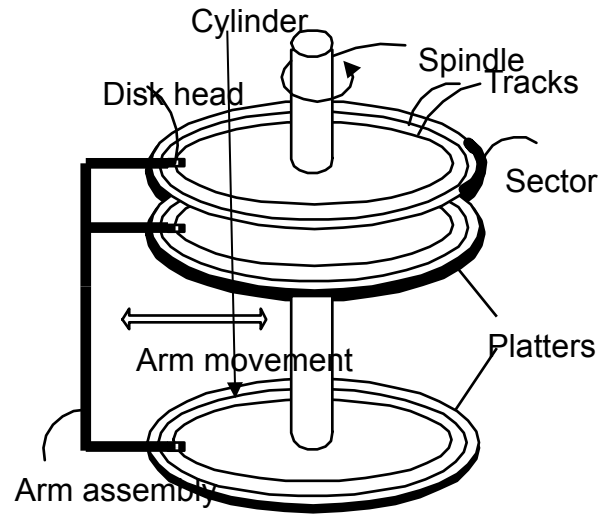
Course Announcements

- Course evaluations are online soon-please fill out 😊
 - We want your feedback to improve the course!
 - Tell us what you liked and didn't!
 - I read **every** evaluation.
- Project 3 is due on Thursday—No late days! We grade that night!
- PS#3 is being graded right now!
- Thursday class is Matei Zaharia. ***Mandatory guest lecture!***

High-Level: Lecture 11

- The ***buffer*** & simplified filesystem model
- Shift to ***IO Aware*** algorithms
- The ***external merge algorithm***

High-level: Disk vs. Main Memory



Disk:

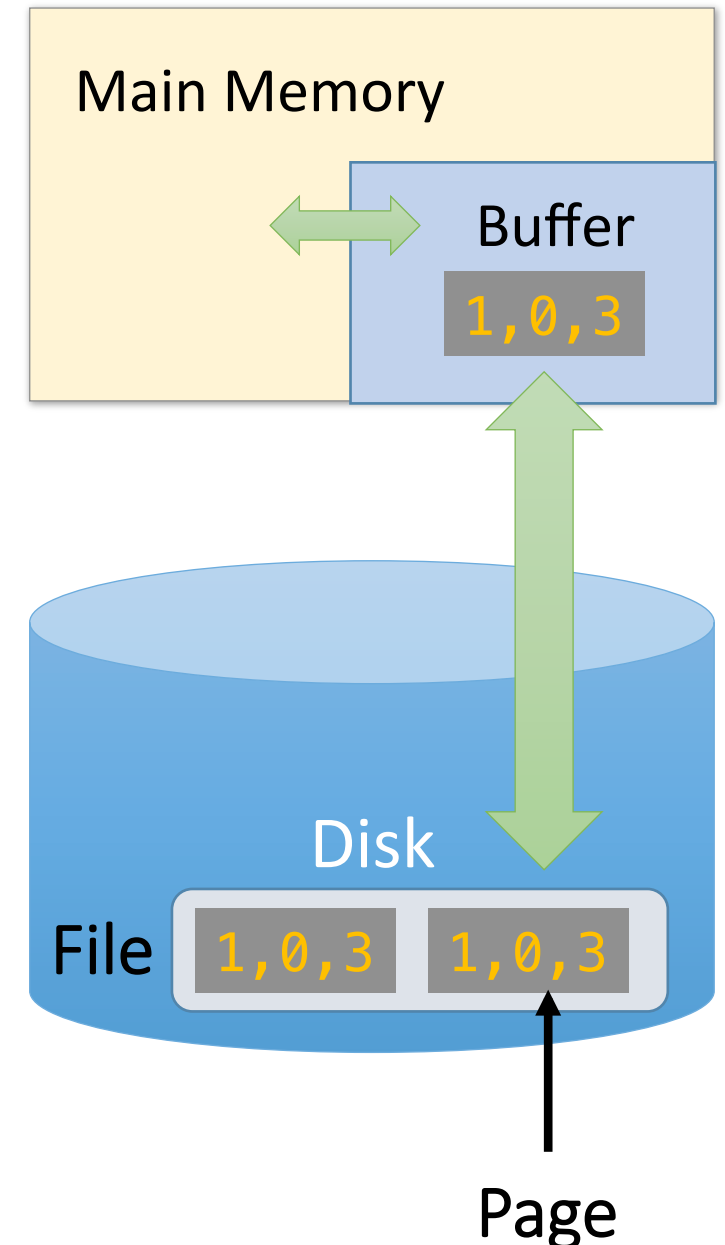
- **Slow:** Sequential *block* access
 - Read a blocks (not byte) at a time, so sequential access is cheaper than random
 - **Disk read / writes are expensive!**
- **Durable:** We will assume that once on disk, data is safe!
- **Cheap**

Random Access Memory (RAM) or Main Memory:

- **Fast:** Random access, byte addressable
 - ~10x faster for sequential access
 - ~100,000x faster for random access!
- **Volatile:** Data can be lost if e.g. crash occurs, power goes out, etc!
- **Expensive:** For \$100, get 16GB of RAM vs. 2TB of disk!

The Buffer

- A **buffer** is a region of physical memory used to store *temporary data*
 - *Key Idea*: Reading / writing to disk is SLOW, need to cache data in main memory
 - Can **read** into buffer, **flush** back to disk, **release** from buffer
- DBMS manages its own buffer for various reasons (better control of eviction policy, force-write log, etc.)
- We use a simplified model:
 - A **page** is a fixed-length array of memory; **pages are the unit that is read from / written to disk**
 - A **file** is a variable-length list of pages on disk



IO Aware

- Key idea: Reading from / writing to disk- e.g. ***IO operations***- is ***thousands*** of times slower than any operation in memory
 - → We consider a class of algorithms which try to minimize IO, and *effectively ignore cost of operations in main memory*

“IO aware” algorithms!

External Merge Algorithm

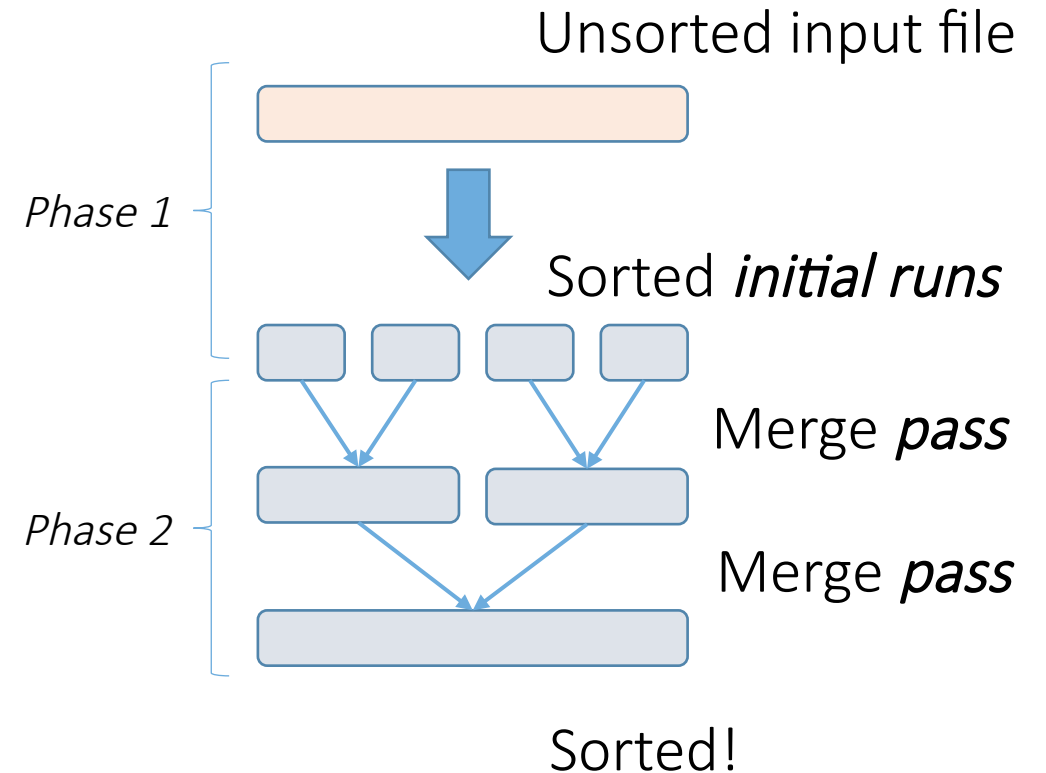
- **Goal:** Merge sorted files that are much bigger than buffer
- **Key idea:** Since the input files are sorted, we always know which file to read from next!

- **Details:**

Given:	$B+1$ buffer pages
Input:	B sorted files, $F_1, \dots, F_B$, where F_i has $P(F_i)$ pages
Output:	One merged sorted file
IO COST:	$2 * \sum_{i=1}^B P(F_i)$ (Each page is read & written once)

External Merge Sort Algorithm

- **Goal:** Sort a file that is much bigger than the buffer
- **Key idea:**
 - *Phase 1:* Split file into smaller chunks (“initial runs”) which can be sorted in memory
 - *Phase 2:* Keep merging (do “passes”) using external merge algorithm until one sorted file!



External Merge Sort Algorithm

Given:	$B+1$ buffer pages	
Input:	Unsorted file of length N pages	
Output:	The sorted file	
IO COST:	$2N(\lceil \log_{B+1} \lceil N/(B+1) \rceil \rceil + 1)$	Phase 1: Initial runs of length $B+1$ are created • There are $\lceil N/(B+1) \rceil$ of these • The IO cost is $2N$ Phase 2: We do passes of B-way merge until fully merged • Need $\lceil \log_{B+1} \lceil N/(B+1) \rceil \rceil$ passes • The IO cost is $2N$ per pass

Repacking Optimization for Ext. Merge Sort

- **Goal:** Create larger initial runs
- **Key Idea:** Keep loading unsorted pages, writing out next-largest values, and “repacking” for as long as possible!
 - *Guaranteed to do at least as well as our previous method of loading & doing quicksort*
- **IO Cost:** On average, we will create initial runs of size $\sim 2(B+1)$

$$2N(\lceil \log \downarrow B \rceil \lceil N/B + 1 \rceil + 1)$$



$$2N(\lceil \log \downarrow B \rceil \lceil N/2(B+1) \rceil + 1)$$

High-Level: Lecture 12

- Indexes Part I: Basics
- B+ Trees
- Clustered vs. unclustered

Indexes

- An index on a file speeds up selections on the search key fields for the index.
 - Where the *search key* could be any subset of fields, and does **not** need to be the same as *key of a relation*

By_Yr_Index

Published	BID
1866	002
1869	001
1877	003

Russian_Novels

BID	Title	Author	Published	Full_text
001	<i>War and Peace</i>	Tolstoy	1869	...
002	<i>Crime and Punishment</i>	Dostoyevsky	1866	...
003	<i>Anna Karenina</i>	Tolstoy	1877	...

By_Author_Title_Index

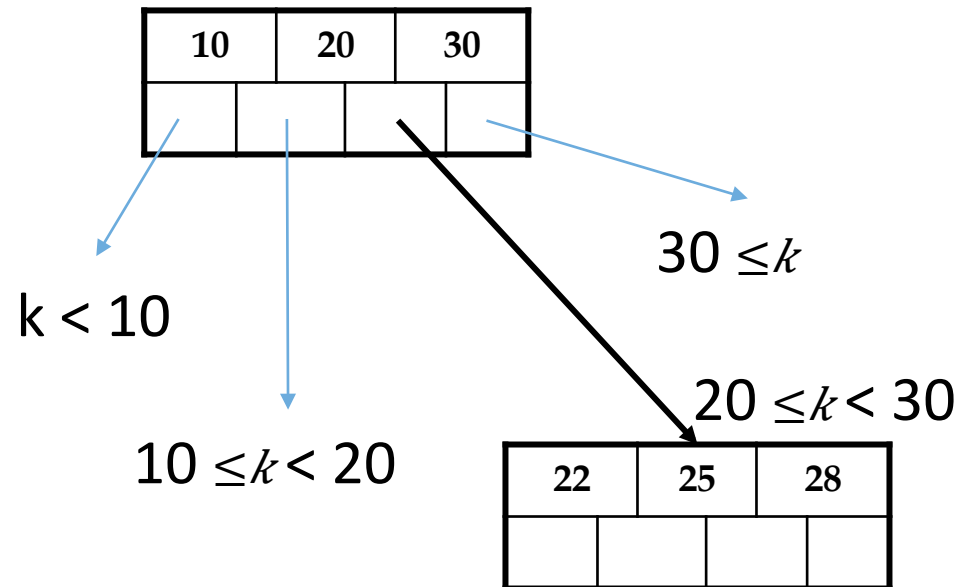
Author	Title	BID
Dostoyevsky	Crime and Punishment	002
Tolstoy	Anna Karenina	003
Tolstoy	War and Peace	001

Note this is the logical setup, not how data is actually stored!

An index is covering for a specific query if the index contains all the needed attributes

B+ Tree Basics

Non-leaf or *internal* node



Parameter d = the degree

Each *non-leaf* (“interior”) **node** has $\geq d$ and $\leq 2d$ **keys***

The n keys in a node define $n+1$ ranges

**except for root node, which can have between 1 and $2d$ keys*

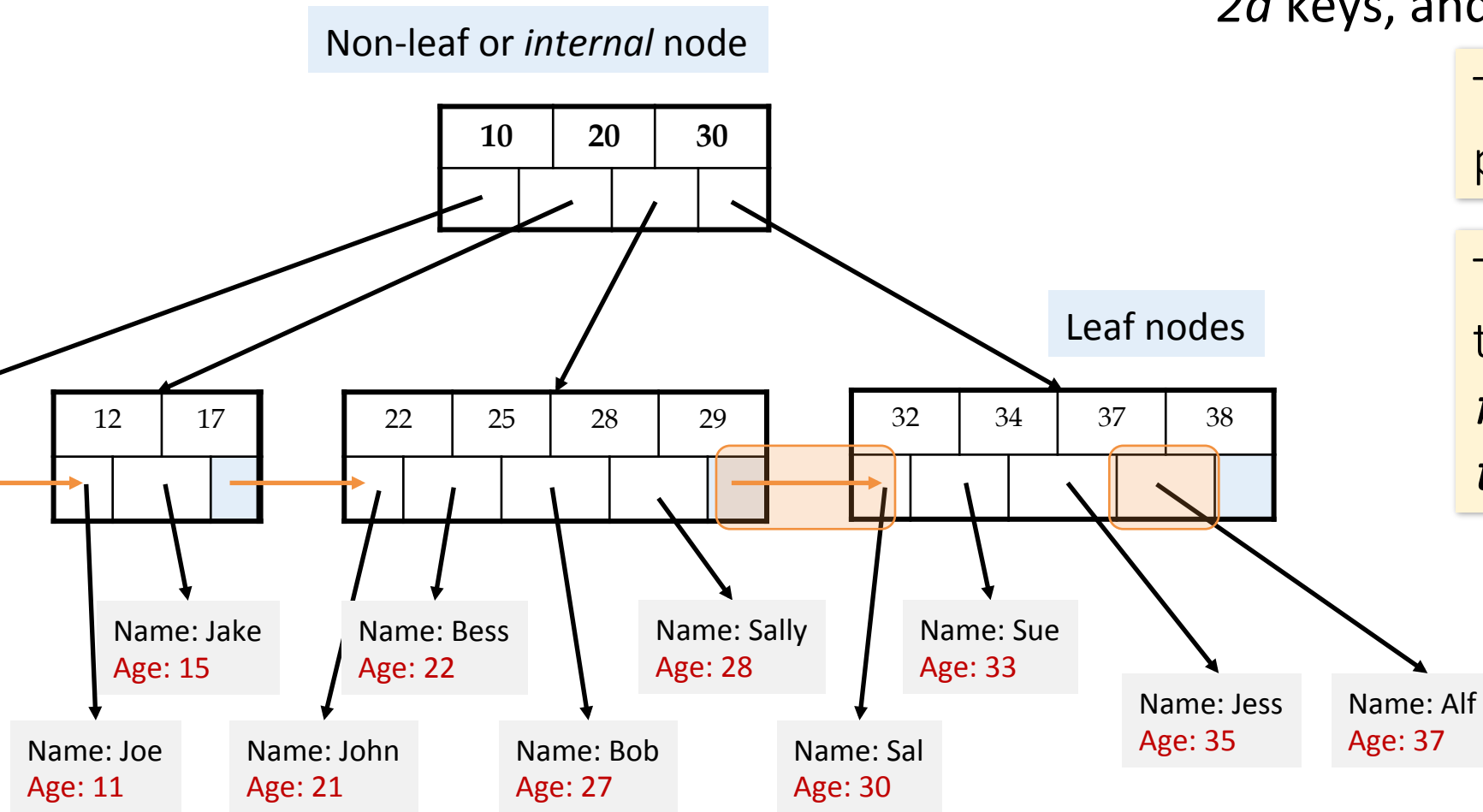
For each range, in a *non-leaf* node, there is a **pointer** to another node with keys in that range

B+ Tree Basics

Leaf nodes also have between d and $2d$ keys, and are different in that:

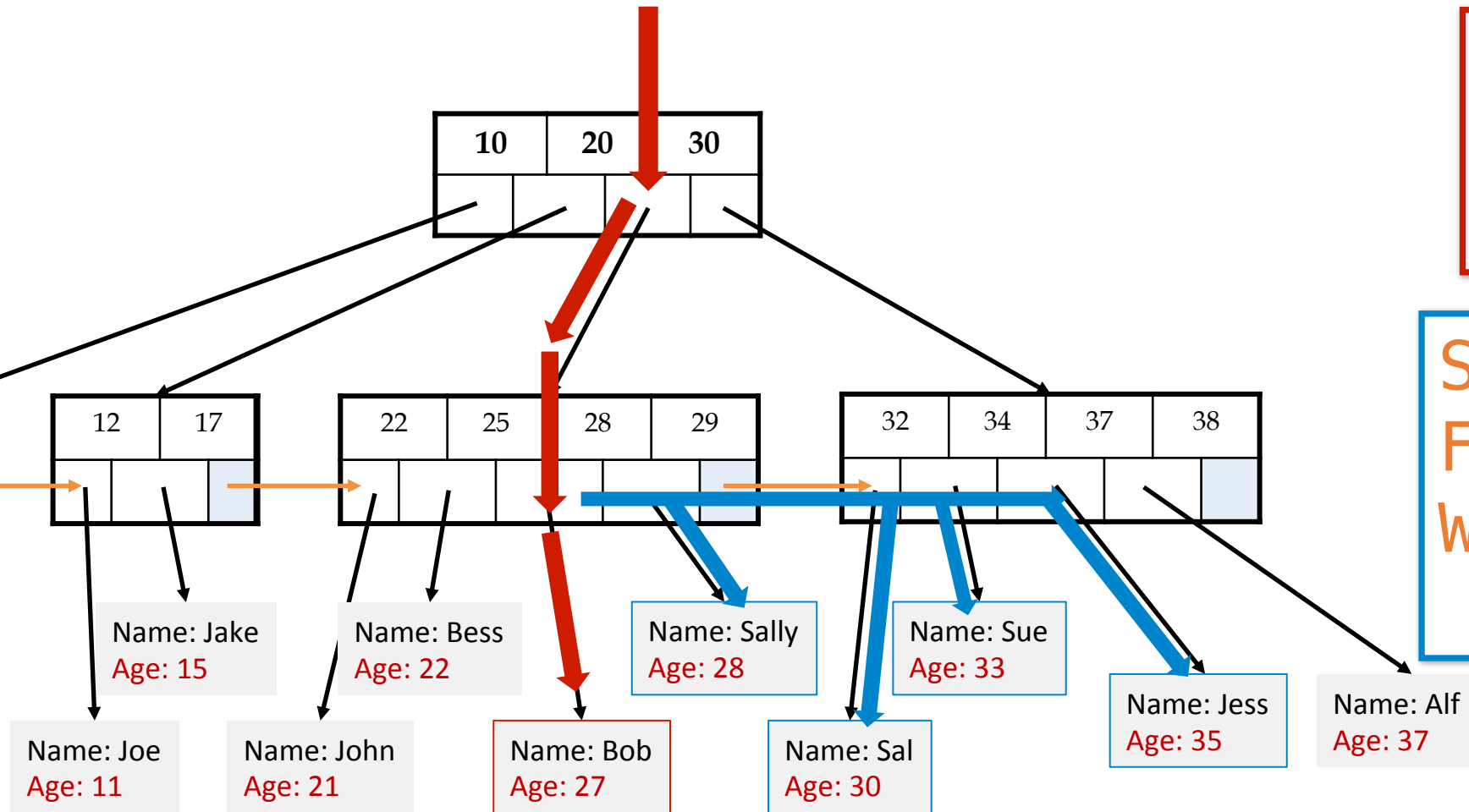
Their key slots contain pointers to data records

They contain a pointer to the next leaf node as well, *for faster sequential traversal*



See L14-15:17-18!

Searching a B+ Tree



```
SELECT name
FROM   people
WHERE  age = 27
```

```
SELECT name
FROM   people
WHERE  27 <= age
AND    age <= 35
```

B+ Tree Range Search

Note that exact search is just a special case of range search ($R = 1$)

- **Goal:** Get the results set of a range (or exact) query with minimal IO
- **Key idea:**
 - A B+ Tree has high **fanout** ($d \approx 10^2 - 10^3$), which means it is very shallow $\rightarrow$ we can get to the right root node within a few steps!
 - Then just traverse the leaf nodes using the horizontal pointers
- **Details:**
 - One node per page (thus page size determines d)
 - Fill only some of each node's slots (the **fill-factor**) to leave room for insertions
 - We can keep some levels of the B+ Tree in memory!

The fanout f is the number of pointers coming out of a node. Thus:

$$d+1 \leq f \leq 2d+1$$

Note that we will often approximate f as constant across nodes!

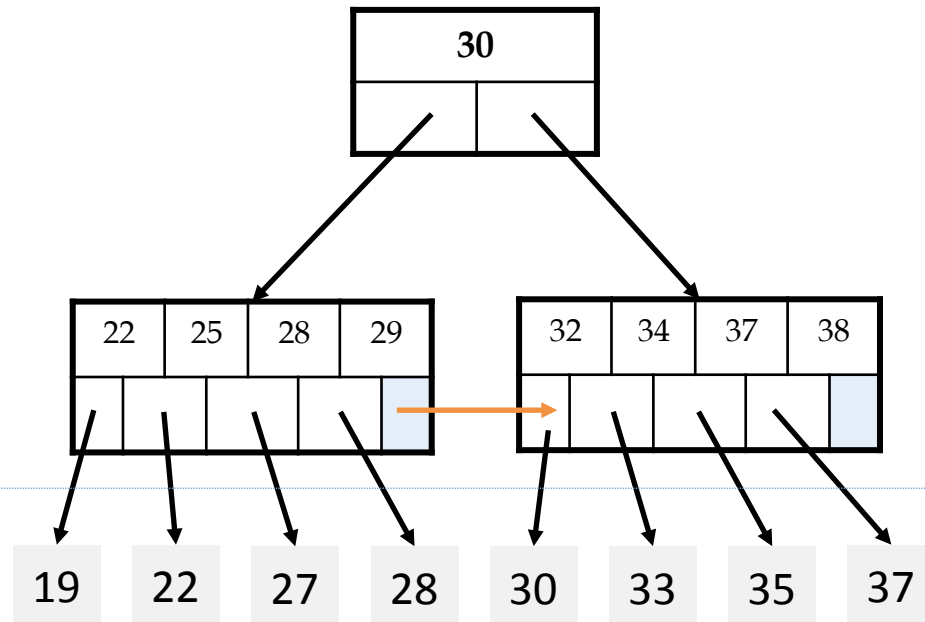
We define the height of the tree as counting the root node. Thus, *given constant fanout f* , a tree of height h can index f^h pages and has f^{h-1} leaf nodes

See L14-15:22-24!

B+ Tree Range Search

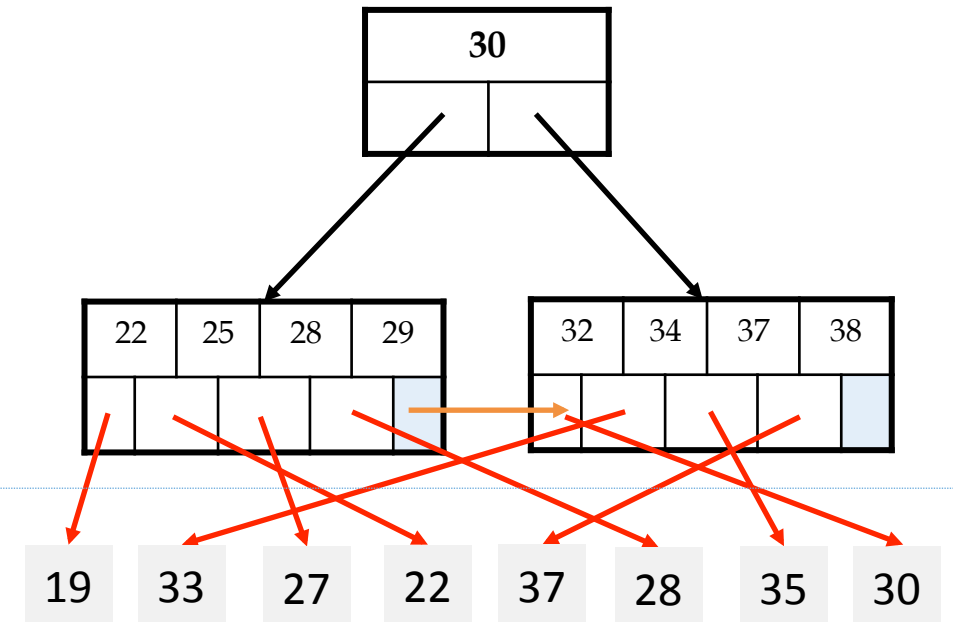
Given:	- Parameter d - Fill-factor F B available pages in buffer - A B+ Tree over N pages f is the fanout $[d+1, 2d+1]$	
Input:	A a range query.	
Output:	The R values that match	
IO COST:	$\lceil \log_{\lfloor f \rfloor} N/F \rceil - LB + \mathbf{Cost}(Out)$ where $B \geq \sum_{l=0}^{LB-1} \lceil f^l \rceil$	Depth of the B+ Tree: For each level of the B + Tree we read in one node = one page # of levels we can fit in memory: These don't cost any IO! This equation is just saying that the sum of all the nodes for L_B levels must fit in buffer

Clustered vs. Unclustered Index



Clustered

1 Random Access IO + Sequential IO
(# of pages of answers)



Unclustered

Random Access IO for each **value**
(i.e. # of tuples in answer)

Clustered can make a *huge* difference for range queries!

High-Level: Lectures 14-15

- Join Algorithms:
 - Nested Loop Join Variants: NLJ, BNLJ, INLJ
 - SMJ
 - Hash Join
- Lecture 15 walks through in detail on the board.
 - Board discussion in the review slides, here...

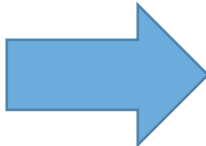
Joins: Example

 $R \bowtie S$

```
SELECT R.A, B, C, D
FROM   R, S
WHERE  R.A = S.A
```

Example: Returns all pairs of tuples $r \in R, s \in S$ such that $r.A = s.A$

R			S					
A	B	C	A	D				
1	0	1	3	7				
2	3	4	2	2				
2	5	2	2	3				
3	1	1						



A	B	C	D
2	3	4	2
2	3	4	3
2	5	2	2
2	5	2	3
3	1	1	7

Join Algorithms: Overview

For $R \bowtie S$ on A

- NLJ: An example of a *non*-IO aware join algorithm
- BNLJ: Big gains just by being IO aware & reading in chunks of pages!

Quadratic in $P(R)$, $P(S)$
i.e. $O(P(R) * P(S))$

- SMJ: Sort R and S , then scan over to join!
- HJ: Partition R and S into buckets using a hash function, then join the (much smaller) matching buckets

Given sufficient buffer space, *linear* in $P(R)$, $P(S)$
i.e. $\sim O(P(R) + P(S))$

By only supporting equijoins & taking advantage of this structure!

Nested Loop Join (NLJ)

```
Compute  $R \bowtie S$  on  $A$ :  
  for  $r$  in  $R$ :  
    for  $s$  in  $S$ :  
      if  $r[A] == s[A]$ :  
        yield  $(r, s)$ 
```

Note that IO cost based on number of *pages* loaded, not number of tuples!

Cost:

$$P(R) + T(R) * P(S) + \text{OUT}$$

1. Loop over the tuples in R
2. For every tuple in R , loop over all the tuples in S
3. Check against join conditions
4. **Write out (to page, then when page full, to disk)**

Have to read *all of S* from disk for *every tuple in R !*

Block Nested Loop Join (BNLJ)

Given $B+1$ pages of memory

Compute $R \bowtie S$ on A :

```

for each B-1 pages pr of R:
  for page ps of S:
    for each tuple r in pr:
      for each tuple s in ps:
        if r[A] == s[A]:
          yield (r,s)
  
```

Again, OUT could be bigger than $P(R)*P(S)$... but usually not that bad

Cost:

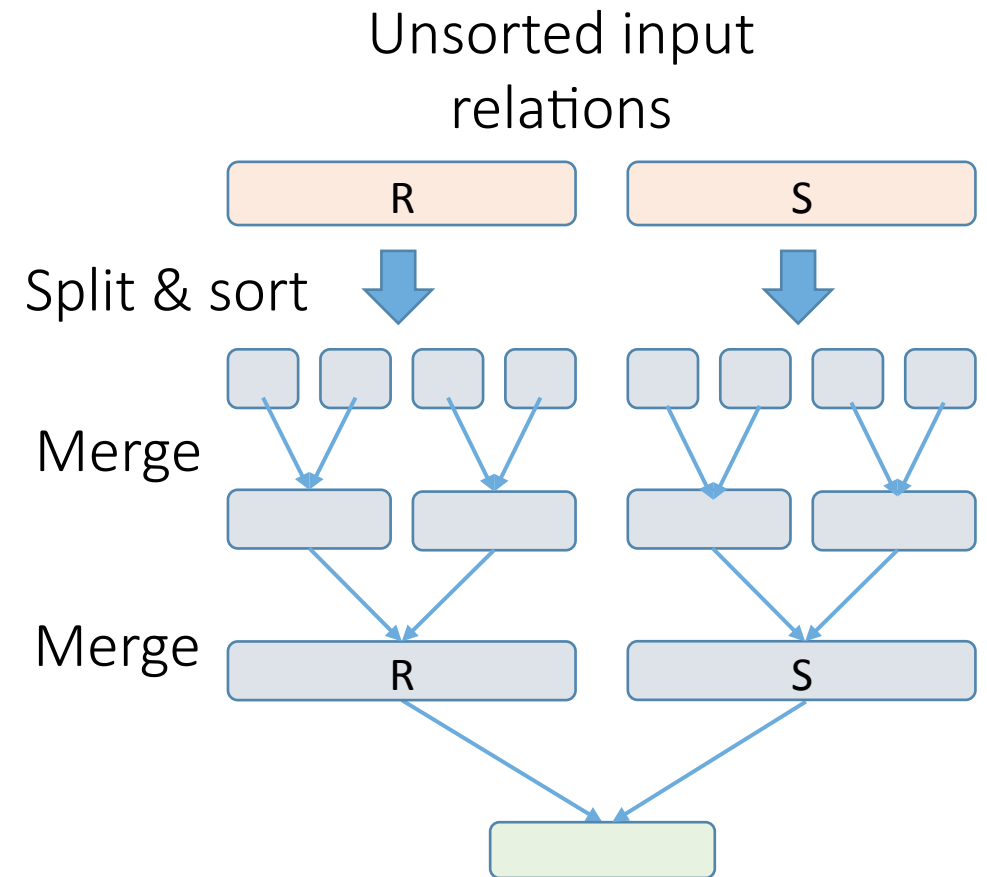
$$P(R) + P(R)/B - 1 P(S) + OUT$$

1. Load in B-1 pages of R at a time (leaving 1 page each free for S & output)
2. For each (B-1)-page segment of R, load each page of S
3. Check against the join conditions

4. Write out

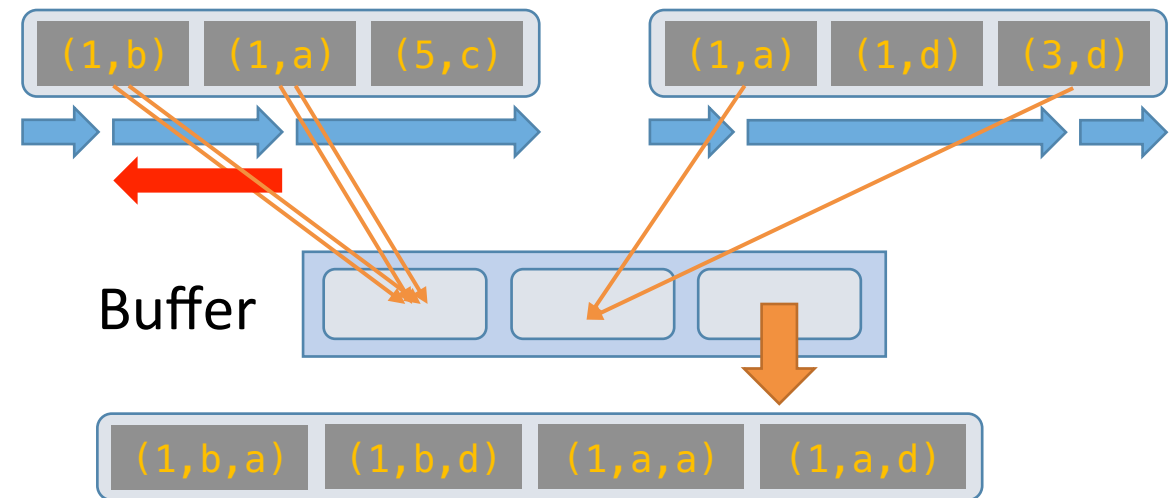
Sort Merge Join (SMJ)

- **Goal:** Execute $R \bowtie S$ on A
- **Key Idea:** We can sort R and S, then just scan over them!
- **IO Cost:**
 - *Sort phase:* $\text{Sort}(R) + \text{Sort}(S)$
 - *Merge / join phase:* $\sim P(R) + P(S) + \text{OUT}$
 - *Can be worse though- see next slide!*



SMJ: Backup

- Without any duplicates:
 - We just scan over R and S once each $\rightarrow P(R) + P(S)$
- However, if there are duplicates, we may have to **back up** and re-read parts of the file
 - In worst case have to read in $P(R) * P(S)$!
 - In worst case, output is $T(R) * T(S)$
 - *Usually not that bad...*



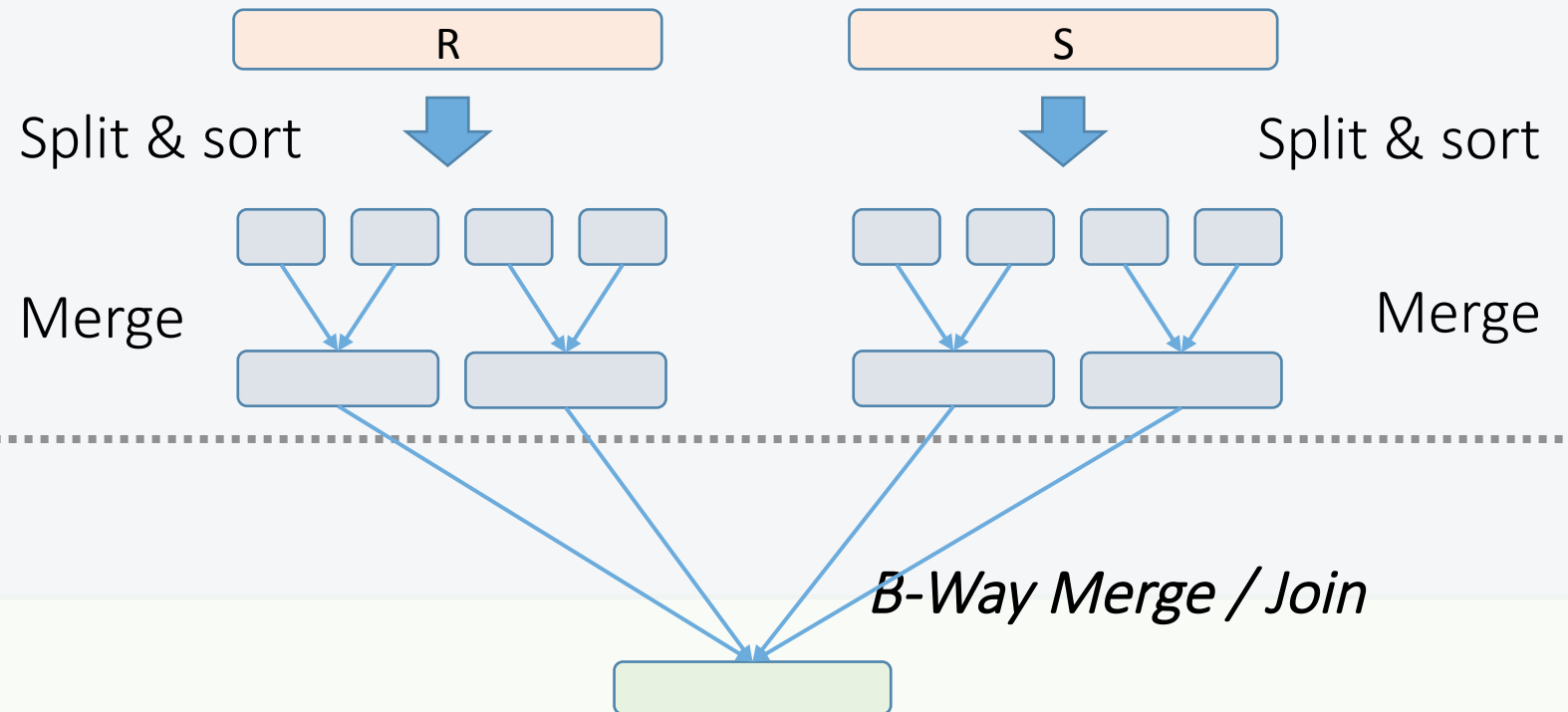
Simple SMJ Optimization

Given $B+1$ buffer pages

Sort Phase
(Ext. Merge Sort)

$\leq B$ total runs

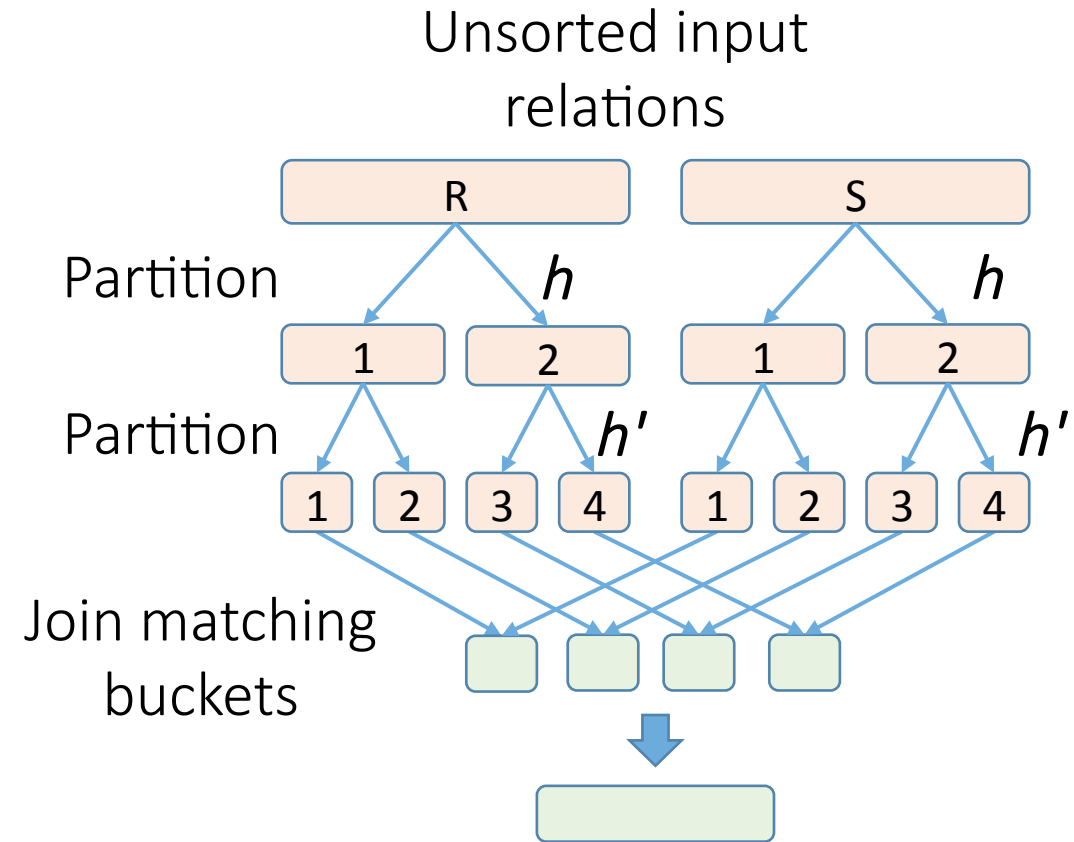
Unsorted input relations



This allows us to "skip" the last sort & save $2(P(R) + P(S))!$

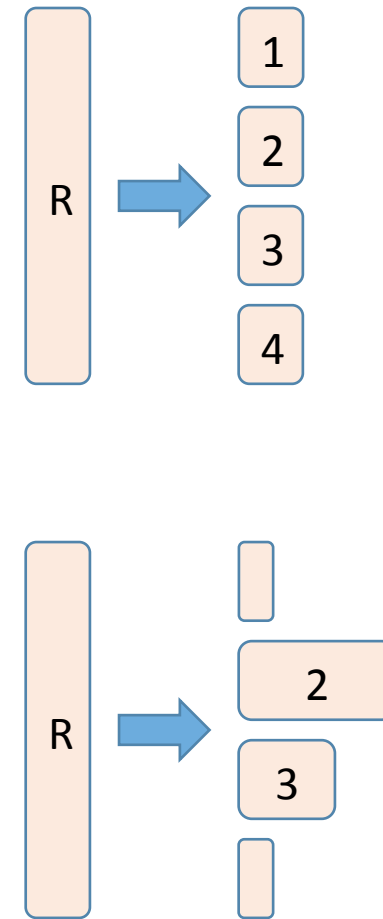
Hash Join

- **Goal:** Execute $R \bowtie S$ on A
- **Key Idea:** We can partition R and S into buckets by hashing the join attribute- then just join the pairs of (small) matching buckets!
- **IO Cost:**
 - *Partition phase:* $2(P(R) + P(S))$ each pass
 - *Join phase:* Depends on size of the buckets... can be $\sim P(R) + P(S) + \text{OUT}$ if they are small enough!
 - **Can be worse though- see next slide!**



HJ: Skew

- Ideally, our hash functions will partition the tuples *uniformly*
- However, hash collisions and *duplicate join key attributes* can cause **skew**
 - For hash collisions, we can just partition again with a new hash function
 - Duplicates are just a problem... (Similar to in SMJ!)



Overview: SMJ vs. HJ

SMJ

HJ

Note:
Ext.
Merge
Sort!

- We create **initial sorted runs**
- We keep **merging** these runs until we have one sorted merged run for R, S
- We scan over R and S to complete the **join**

- We keep **partitioning** R and S into progressively smaller buckets using hash functions $h, h', h'' \dots$
- We **join** matching pairs of buckets (using BNLJ)

How many of these passes do we need to do?

$R \propto S \text{ on } A$

How many passes do we need?

SMJ

HJ

Initial
sorted
runs

# of passes	Length of runs	# of runs
0	1	N
1	$B+1$	$\lceil N/B+1 \rceil$
2	$B(B+1)$	$1/B \lceil N/B+1 \rceil$
...	...	...
$k+1$	$B^k(B+1)$	$1/B^{k+1} \lceil N/B+1 \rceil$

# of passes	Avg. bucket size	# of buckets
0	N	1
1	$\lceil N/B \rceil$	B
2	$1/B \lceil N/B \rceil$	B^2
...	...	...
$k+1$	$1/B^{k+1} \lceil N/B \rceil$	B^{k+1}

Each
pass,
we get:

Fewer, longer runs by a factor of B

More, smaller buckets by a factor of B

Each pass costs $2(P(R)+P(S))$

How many passes do we need?

SMJ

# of passes	Length of runs	# of runs
$k+1$	$B^k(B+1)$	$1/B \uparrow k \lceil N/(B+1) \rceil$

If (# of runs of R) + (# of runs of S) $\leq B$, then we are ready to complete the join in one pass*:

$$B \geq P(R)/B^k(B+1) + P(S)/B^k(B+1)$$

$$B \uparrow k+1 (B+1) \geq P(R) + P(S)$$

*Using the 'optimization' on slide 25

HJ

# of passes	Avg. bucket size	# of buckets
$k+1$	$1/B \uparrow k \lceil N/B \rceil$	B^{k+1}

If *one of* the relations has bucket size $\leq B-1$, then we have partitioned enough to complete the join with single-pass BNLJ:

$$B-1 \geq \min\{P(R), P(S)\}/B \uparrow k+1$$

$$B \uparrow k+1 (B-1) \geq \min\{P(R), P(S)\}$$

How many buffer pages for nice behavior?

Let's consider what B we'd need for $k+1 = 1$ passes (plus the final join):

SMJ

$$B(B+1) \geq P(R) + P(S)$$

If we use repacking, then we can satisfy the above if approximately:

$$B^2 \geq \max\{P(R), P(S)\}$$

HJ

$$B(B-1) \geq \min\{P(R), P(S)\}$$

So approximately:

$$B^2 \geq \min\{P(R), P(S)\}$$

$\rightarrow$ Total IO Cost = $3(P(R) + P(S)) + OUT!$

Overview: SMJ vs. HJ

- HJ:
 - PROS: Nice linear performance is dependent on the *smaller relation*
 - CONS: Skew!
- SMJ:
 - PROS: Great if relations are already sorted; output is sorted either way!
 - CONS:
 - Nice linear performance is dependent on the *larger* relation
 - Backup!

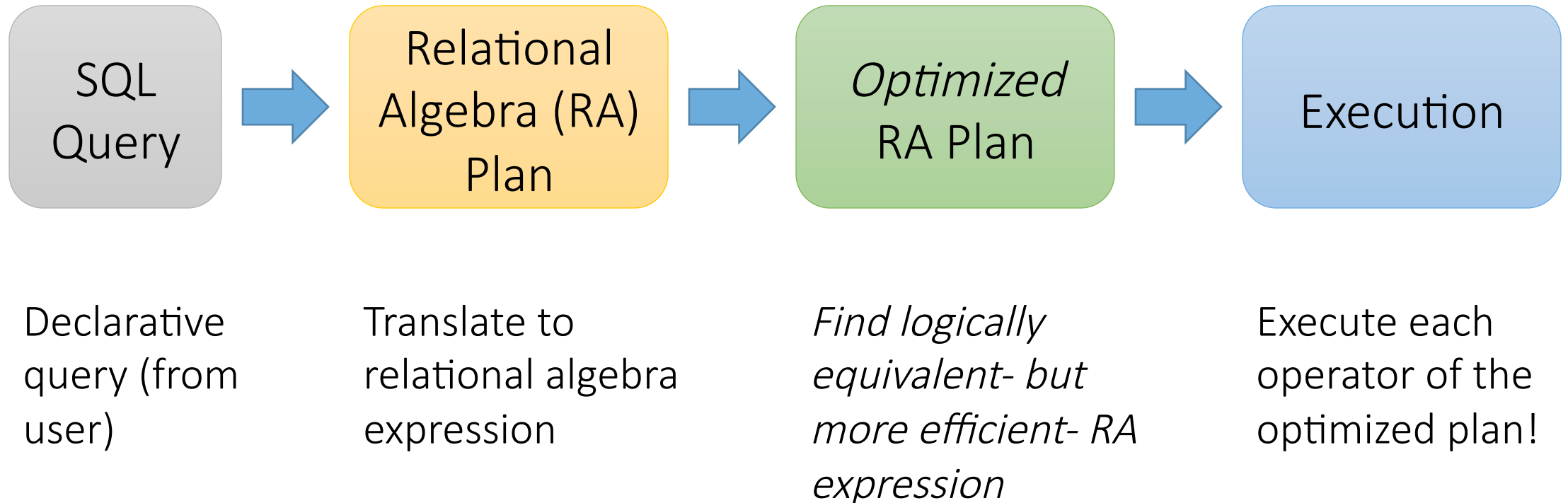
High-Level: Lecture 16

- Overall RDBMS architecture
- The Relational Model
- Relational Algebra

*Check out the
Relational Algebra
practice exercises
notebook!!*

RDBMS Architecture

How does a SQL engine work ?



The Relational Model: Data

An attribute (or column) is a typed data entry present in each tuple in the relation

Student

sid	name	gpa
001	Bob	3.2
002	Joe	2.8
003	Mary	3.8
004	Alice	3.5

The number of tuples is the cardinality of the relation

A tuple or row (or *record*) is a single entry in the table having the attributes specified by the schema

A relational instance is a *set* of tuples all conforming to the same *schema*

The number of attributes is the arity of the relation

Relational Algebra (RA)

- Five **basic** operators:

1. Selection: σ
2. Projection: Π
3. Cartesian Product: $\times$
4. Union: $\cup$
5. Difference: $-$

- Derived or auxiliary operators:

- Intersection, complement
- Joins (natural, equi-join, theta join, semi-join)
- Renaming: ρ
- Division

1. Selection (σ)

- Returns all tuples which satisfy a condition
- Notation: $\sigma_c(R)$
- The condition c can be $=$, $<$, $>$, $<>$

Students(sid, sname, gpa)

SQL:

```
SELECT *  
FROM Students  
WHERE gpa > 3.5;
```



RA:
 $\sigma_{gpa > 3.5}(Students)$

2. Projection (Π)

- Eliminates columns, then removes duplicates
- Notation: $\Pi_{A1, \dots, An}(R)$

`Students(sid, sname, gpa)`

SQL:

```
SELECT DISTINCT  
    sname,  
    gpa  
FROM Students;
```



RA:
 $\Pi_{\downarrow sname, gpa}(Students)$

3. Cross-Product ($\times$)

- Each tuple in R1 with each tuple in R2
- Notation: $R1 \times R2$
- Rare in practice; mainly used to express joins

```
Students(sid,sname,gpa)  
People(ssn,pname,address)
```

SQL:

```
SELECT *  
FROM Students, People;
```



RA:
 $Students \times People$

Renaming (ρ)

- Changes the schema, not the instance
- A 'special' operator- neither basic nor derived
- Notation: $\rho_{B1,\dots,Bn}(R)$
- **Note: this is shorthand for the proper form (since names, not order matters!):**
 - $\rho_{A1 \rightarrow B1, \dots, An \rightarrow Bn}(R)$

`Students(sid, sname, gpa)`

SQL:

```
SELECT
  sid AS studId,
  sname AS name,
  gpa AS gradePtAvg
FROM Students;
```



RA:
 $\rho_{\downarrow studId, name, gradePtAvg}(Students)$

We care about this operator *because* we are working in a *named perspective*

Natural Join ($\bowtie$)

- Notation: $R_1 \bowtie R_2$
- Joins R_1 and R_2 on *equality of all shared attributes*
 - If R_1 has attribute set A , and R_2 has attribute set B , and they share attributes $A \cap B = C$, can also be written: $R_1 \bowtie_C R_2$
- Our first example of a *derived* RA operator:
 - Meaning: $R_1 \bowtie R_2 = \Pi_{A \cup B}(\sigma_{C=D}(\rho_{\downarrow C \rightarrow D}(R_1) \times R_2))$
 - Where:
 - The rename $\rho_{\downarrow C \rightarrow D}$ renames the shared attributes in one of the relations
 - The selection $\sigma_{C=D}$ checks equality of the shared attributes
 - The projection $\Pi_{A \cup B}$ eliminates the duplicate common attributes

```
Students(sid, name, gpa)
People(ssn, name, address)
```

SQL:

```
SELECT DISTINCT
    ssid, S.name, gpa,
    ssn, address
FROM
    Students S,
    People P
WHERE S.name = P.name;
```



RA:
 $Students \bowtie People$

Converting SFW Query -> RA

```

SELECT DISTINCT A1, ..., An
FROM           R1, ..., Rm
WHERE          c1 AND ... AND ck;
  
```



$$\Pi_{A_1, \dots, A_n} (\sigma_{c_1} \dots \sigma_{c_k} (R_1 \bowtie \dots \bowtie R_m))$$

Why must the selections “happen before” the projections?

High-Level: Lecture 17

- Logical optimization
- Physical optimization
 - Index selections
 - IO cost estimation

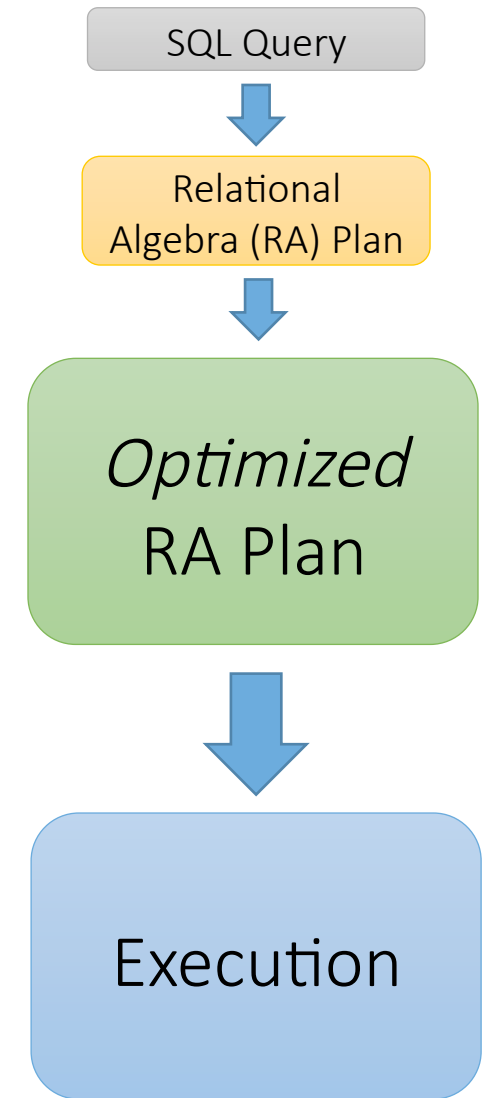
Logical vs. Physical Optimization

- **Logical optimization:**

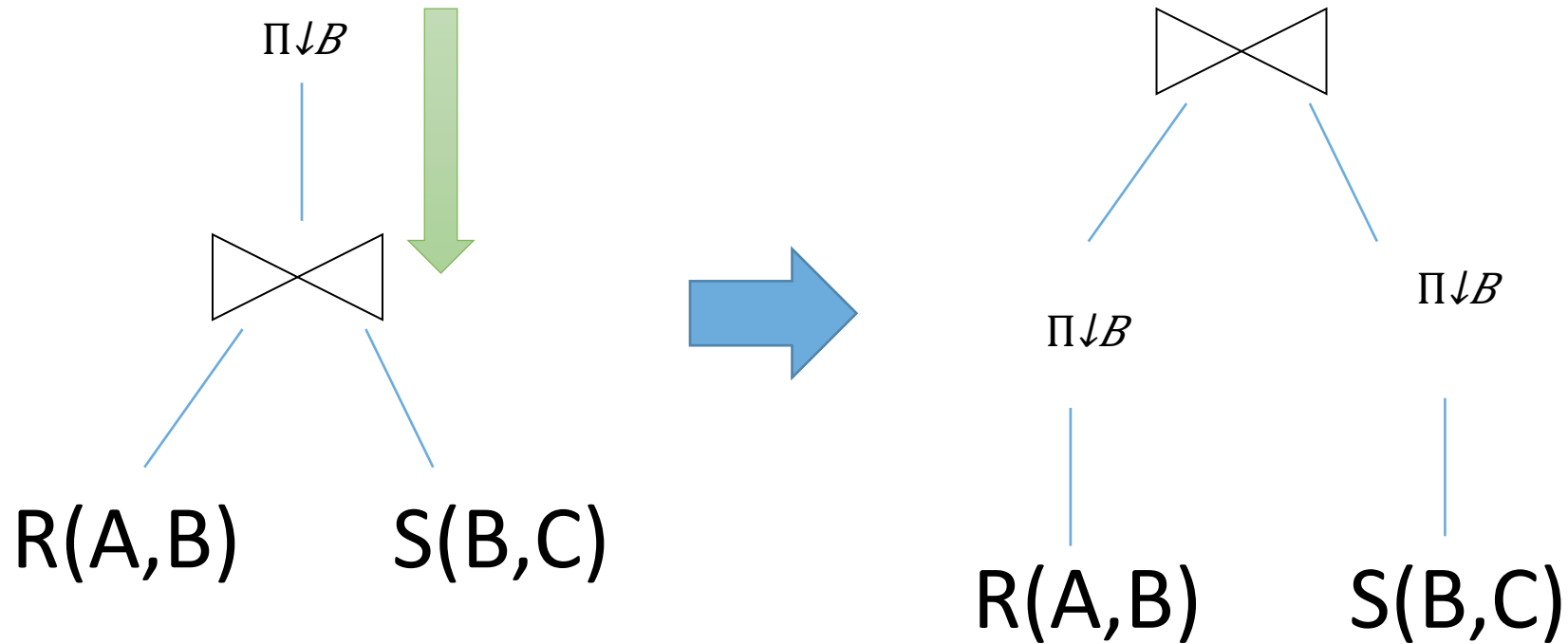
- Find equivalent plans that are more efficient
- *Intuition: Minimize # of tuples at each step by changing the order of RA operators*

- **Physical optimization:**

- Find algorithm with lowest IO cost to execute our plan
- *Intuition: Calculate based on physical parameters (buffer size, etc.) and estimates of data size (histograms)*

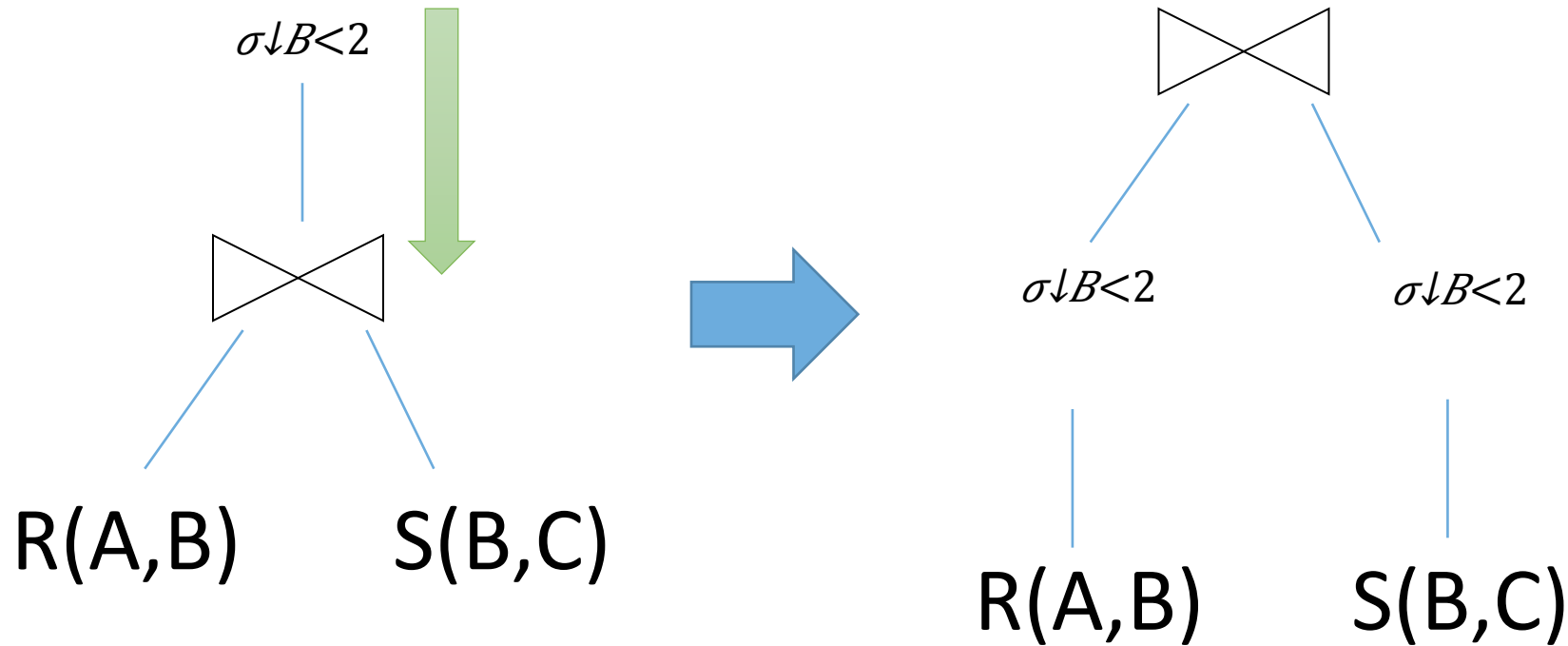


Logical Optimization: “Pushing down” projection



Why might we prefer this plan?

Logical Optimization: “Pushing down” selection



Why might we prefer this plan?

RA commutators

- The basic commutators:
 - Push **projection** through **(1) selection, (2) join**
 - Push **selection** through **(3) selection, (4) projection, (5) join**
 - *Also: Joins can be re-ordered!*
- Note that this is not an exhaustive set of operations
 - This covers *local re-writes*; *global re-writes possible but much harder*

This simple set of tools allows us to greatly improve the execution time of queries by optimizing RA plans!

Index Selection

Input:

- Schema of the database
- **Workload description:** set of (query template, frequency) pairs

Goal: Select a set of indexes that minimize execution time of the workload.

- Cost / benefit balance: Each additional index may help with some queries, but requires updating

This is an optimization problem!

IO Cost Estimation via Histograms

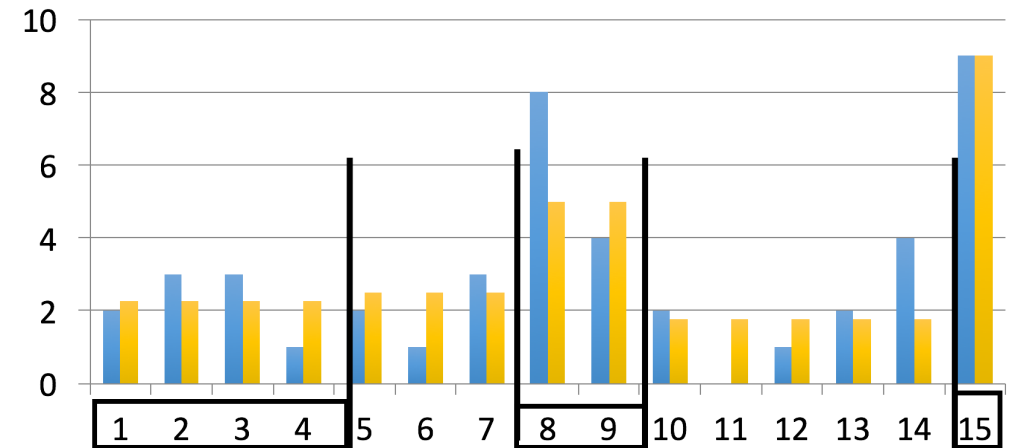
- For **index selection**:
 - What is the cost of an index lookup?
- Also for **deciding which algorithm to use**:
 - Ex: To execute $R \bowtie S$, which join algorithm should DBMS use?
 - What if we want to compute $\sigma_{A > 10}(R) \bowtie \sigma_{B = 1}(S)$?
- In general, we will need some way to ***estimate intermediate result set sizes***

Histograms provide a way to efficiently store estimates of these quantities

Histogram types

Equi-depth

All buckets contain roughly the same number of items (total frequency)



Equi-width

All buckets roughly the same width

